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A Fast Ethernet FSO Link Performance Under the Fog Controlled Environment

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Abstract: A fast Ethernet 100BASE-TX FSO link performance is evaluated within a dedicated indoor atmospheric chamber performing BER of $<10^{-6}$ under thick fog controlled condition corresponding to an outdoor visibility range higher than 70 m.

OCIS codes: (200.2605) Free-space optical communication; (010.1300) Atmospheric propagation

1. Introduction

Over the last decade, a number of bandwidth hungry applications and services have appeared, e.g., HD streaming, mobile broadband and online gaming. To address this high bandwidth demand, ubiquitous and high data-rate access technologies have emerged based on a range of wireless, fibre and optical-wireless technologies. The renewed interest in terrestrial Free-Space Optical (FSO) communications is largely due to a license-free operation, a point-to-point and line-of-sight (LOS) high data-rate transmission capability over long link distances, a low deployment cost and power efficient management characteristics [1]. Moreover, the availability of commercial FSO links offer cost effective full-duplex 1.25 Gbit/s Gigabit Ethernet (GbE) over 500 m link compared with the fibre-based solutions [2, 3], hence offering an alternative complementary technology to the radio based links for the last-mile access. However, the weather and atmospheric conditions can instigate a high outage probability on the FSO link, thus limiting the link range and availability due to a low signal-to-noise ratio (SNR). Amongst many atmospheric constituents, fog is the biggest contributor to the optical attenuation (480 dB/km attenuation in dense maritime fog). This is due to the Mie scattering of the optical beam, which reduces the link visibility particularly near the ground and consequently degrades the link performance [4].

In many cases, depending on the location, environment, etc. assessing the FSO link performance in a real foggy condition may take a very long time and will depend on when fog is present and how long it will last. Thus the need for an indoor fog test bed where measurement could readily be carried under controlled environment. In [5] replication of the atmospheric phenomenon under controlled environments has been analyzed. It is shown that the resemblance of the outdoor conditions depends on the index of refraction structure constant C_n^2 whereas the link margin is related to the scintillation and attenuation. This paper analyzes the performance of a real fast Ethernet (100BASE-TX 100Mbit/s LAN) FSO link under controlled fog conditions. The experiment is carried out using a dedicated indoor atmospheric chamber capable of replicating turbulence and fog. In this paper, the chamber performance is experimentally evaluated for the on-off keying non-return-to-zero (OOK-NRZ), OOK return-to-zero (OOK-RZ) and four pulse position modulation (4-PPM) formats. Then the complete evaluation of the FSO fast Ethernet and Ethernet 10BASE-T link, based on OOK-NRZ signalling with 4B5B coding, over a 12 m link range under controlled fog environment is carried out.

2. Atmospheric chamber concept and set-up

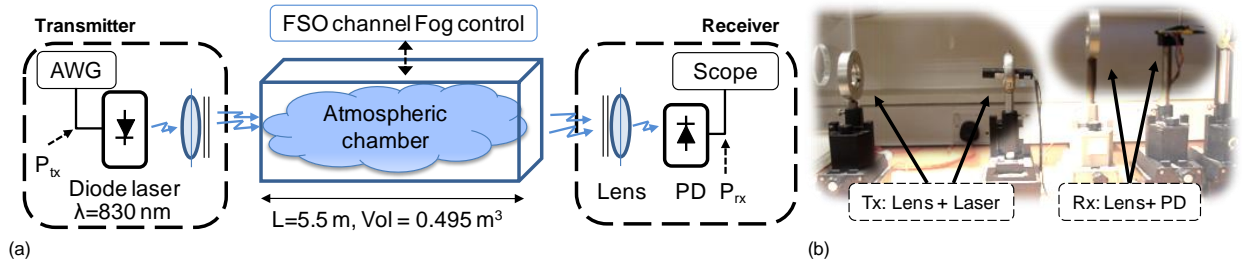


Fig. 1. a) The schematic block diagram of the FSO link set-up, b) the snapshot showing the transmitter and receiver

The atmospheric chamber has a dimension of $550 \times 30 \times 30\text{ cm}^3$, with seven compartments each having a vent to allow air circulation in and out of the chamber, as depicted in Fig. 1. In every compartment a temperature controlled hotplate and fans are included to simulate the effect of the turbulence, wind speed and slow or fast fog on the

propagating optical beam. A fog generator is used to pump fog at a rate of $0.94 \text{ m}^3/\text{s}$ to the chamber. The fog density within the chamber is controlled by a combination of the amount of fog pumped in and the ventilation system. This set up offers the advantage of repeatedly replicating atmospheric weather conditions in a controlled manner without the need for a long observation period in an outdoor environment. The path length through the chamber can be doubled by using reflecting mirrors located on both ends of the chamber. Here we use one mirror to extend the link to 12 m. Note that 12 m link is relatively small compared to the real outdoor link but this will help to increase the dynamic range of the link attenuations. The desired signaling formats (OOK-NRZ, OOK-RZ and 4-PPM) generated using an arbitrary waveform generator (AWG) are used to intensity modulate the laser source. The main setup parameters are summarized in Table I.

TABLE I. FSO link setup parameters

Transmitter front end (Laser + AWG)		Receiver front end (photodiode + lens)	
Operating wavelength	830 nm	Lens focal length	10 cm
Average optical output power	10 mW	Lens diameter	30 mm
Laser modulation depth, m	20%	Photodetector responsivity	0.59 A/W @ 830 nm
Laser 3-dB bandwidth	50 MHz	PD active area	1 mm ²
PRBS length	2^{10} -1 bits	PD half angle view	$\pm 75^\circ$

In order to evaluate the FSO link performance, the Q -factor of the received signal is analyzed for a range of transmittances values T within the $\{0-1\}$ range. T is calculated by comparing the average received optical intensity in the presence and absence of fog, derived from the Beer-Lambert law [6]:

$$T = \frac{I(f)}{I(0)} = \exp(-\beta_\lambda z), \quad (1)$$

where β_λ is the attenuation or the scattering coefficient due to fog, in units of km^{-1} , z is the propagation length and $I(f)$ and $I(0)$ are the average received optical intensities in the presence and absence of fog, respectively. In this case, the link visibility V parameter is derived from the fog attenuation using the Kim's model [7] with a distance shorter than 500 m, where β_λ is defined as:

$$\beta_\lambda = \frac{3.912}{V} \left(\frac{\lambda_{nm}}{550} \right)^{-q}, \quad (2)$$

where the constant q depends on V as given in [7]. Eqs. (1) and (2) relate V and T , thus enabling us to experimentally analyze the performance of the FSO link, Q -factor, in presence of fog.

TABLE II. FSO link characteristics for $\lambda = 830 \text{ nm}$ and $P_{tx} = -1.23 \text{ dBm}$

Fog	Dense	Thick	Moderate	Light	Clear
V (m)	25 – 70	70 - 250	250 - 500	500 - 1000	>1000
T	< 0.36	0.36 - 0.67	0.67 – 0.85	0.85 – 0.92	> 0.92

The scintillation index, defined by the Rytov variance in weak turbulence environments is evaluated in [8]. Using the chamber we experimentally determine the intensity variance of the received optical signal in a weak turbulence regime and then approximate the value of C_n^2 , which is $10^{-11} \text{ m}^{-2/3}$ and is similar to the findings reported in [5]. According to the literature, the link margin M is defined as:

$$M = P_{tx} + S_{pd} - L_{fog} - L_{geo} - L_{dev}, \quad (3)$$

where S_{pd} is the photodetector sensitivity (-36 dBm at 12.5 Mbit/s for bit error rate (BER) $< 10^{-6}$), P_{tx} is the total optical power transmitted, L_{geo} is the geometrical loss, L_{fog} is the loss due to the fog estimated by T , L_{dev} is the transceiver losses due to experimental issues. The link margin for clear conditions is more than 6 dB, which is a typical value for existing commercial outdoor FSO communications with a range up to 2 km.

3. Experimental results and discussions

The FSO link performance for different signaling formats is evaluated in the presence of fog at 25 and 50 Mbit/s base-line data-rates, this is twice and four times that of the 10BASE-T Ethernet bit rate. In order to ensure fair comparison, the average optical transmitted power P_{tx} is maintained constant for all signaling formats. This implies that the amplitude levels and the time-slot duration of the OOK-RZ and 4-PPM are twice and half that of OOK-NRZ, respectively. In this study, a modulating voltage of 250 mV_{p-p} for OOK-NRZ is used corresponding to the transmitted optical power P_{tx} of -1.23 dBm for 25 and 50 Mbit/s base-line data-rates.

The normalized Q -factor (normalized to Q -factor in the absence of fog) against the transmittance at 50 Mbit/s depicted in Fig. 2(a) shows that OOK-RZ and 4-PPM modulation formats are more robust to fog impairments when

compared to OOK-NRZ. Different fog conditions (visibility and transmittance) displayed at Table II are outlined in Fig. 2(a). The Q -factors at $T = 1$ are ~ 36.5 , ~ 33 and ~ 22 at 25 Mbit/s, which reduces to ~ 16 , ~ 18 and ~ 20 at 50 Mbit/s for 4-PPM, OOK-RZ and OOK-NRZ, respectively. Notice a significant reduction in the Q -factor for 4-PPM and OOK-RZ formats due to the 3-dB cut-off frequency of the transmitter laser which is 50 MHz. The behaviours of three modulation schemes under the fog condition are similar. The minimum FSO link availability is defined by the sensitivity of the photoreceiver for a BER $< 10^{-6}$ (Q -factor > 4.7). Fig. 2 shows that it is possible to obtain a Q -factor of > 5 (i.e. BER $< 10^{-6}$) at dense fog conditions for $T > 0.2$ (equivalent to the outdoor attenuation of ~ 380 dB/km) for all the signalling formats, thus assuring the link availability at 50 Mbit/s in poor visibility conditions.

In order to analyze the performance of the FSO link, a pseudo-random bit sequence (PRBS) of $2^{10}-1$ is generated and converted into a 4B5B format prior to transmission through the channel. The baseline data rate are 10 and 100 Mbit/s corresponding to the Ethernet and Fast Ethernet, respectively that results in a line rate of 12.5 Mbit/s and 125 Mbit/s. The Q -factor performance results for the fast Ethernet over 12m for different received optical power P_{rx} and fog conditions are depicted in Figs. 2 (b) and (c).

The comparative study shows a significant drop in the Q -factor from ~ 22 to ~ 7 for Ethernet and Fast Ethernet links, respectively. This is largely due to the bandwidth limitation imposed by the laser source in the experimental setup. Both Ethernet and Fast Ethernet links can operate under the dense fog regime. The measured Q -factor is deteriorated below the minimum requirement of ~ 5 when the transmittance is dropped below 0.1 and 0.2 for Ethernet and Fast Ethernet cases, respectively. From the investigation of the laboratory FSO link, we can predict that the outdoor FSO link can be available for the thick fog condition with a visibility range greater than 70 m. A BER $< 10^{-6}$ can be therefore estimated for the Fast Ethernet outdoor link.

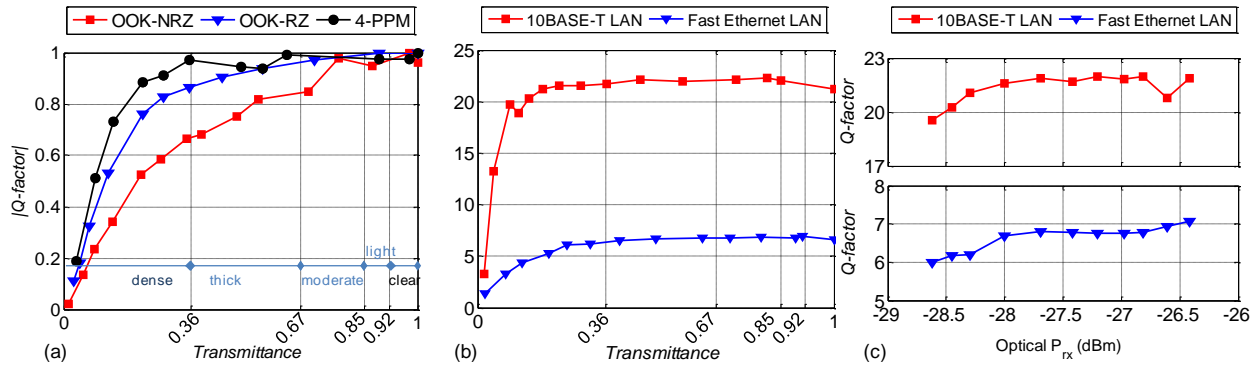


Fig 2. Q -factor against the received optical power and transmittance for a) different modulation schemes b) Ethernet and fast Ethernet at different transmittance and c) at different received optical power

4. Conclusion

The paper has presented the experimental analysis of the Fast Ethernet FSO link in the laboratory fog-controlled condition, which is then used to predict the outdoor links. To the best of our knowledge data rate exceeding 100 Mbit/s is the first to be demonstrated in a laboratory environment. The results obtained is used to determine the availability of the fast Ethernet FSO outdoor link in the dense fog condition when the transmittance $T > 0.2$ (poor visibility). These results demonstrate the feasibility and accuracy of the dedicated atmospheric chamber being used to assess the FSO link performance under fog controlled channel.

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